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RESEARCH ARTICLE

Derivation of physiological inhalation rates in children, adults, and elderly based on nighttime and daytime respiratory parameters

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Abstract

The methodology developed in our previous studies (Brochu *et al.* 2006a–c) for the determination of physiological daily inhalation rates was improved by integrating into the calculation process, both nighttime and daytime respiratory parameters, namely oxygen uptake factors (*H*) and ventilatory equivalents (VQ). *H* values during fasting (0.2057 ± 0.0018 L of O_2/kcal; mean ± SD) and postprandial phases (0.2059 ± 0.0019 L of O_2/kcal) as well as VQ values for subjects at rest (27.4 ± 4.8 to 32.2 ± 3.1, unitless) and during the aggregate daytime activities (29.9 ± 4.2 to 33.7 ± 7.2) were determined and combined with published doubly labeled water measurements for the calculation of daily inhalation rates in normal-weight males and females aged 0.22–96 years ($n = 1235$). Depending upon the unit value chosen, the highest 99th percentiles for inhalation data were found in males aged 35 to <45 years (35.40 m^3/day), 2.6 to <6 months (1.138 m^3/kg-day), and 10 to <16.5 years (22.29 m^3/m^2-day). Means and percentiles expressed in m^3/kg-day as well as in m^3/m^2-day suggest generally higher intakes of air pollutants in children than in adults and in males than in females (in µg/kg-day or µg/m^2-day) for identical exposure concentrations and conditions. For instance, means in boys aged 2.6 to <6 months of 10.99 ± 3.50 m^3/m^2-day and 0.572 ± 0.191 m^3/kg-day are 1.3- and 2.5-folds higher, respectively, than those in adult males 65–96 years old (8.42 ± 2.13 m^3/m^2-day, 0.225 ± 0.059 m^3/kg-day).

Keywords: Daily inhalation rates, oxygen uptake factor, ventilatory equivalent, doubly labeled water, health risk assessment

Introduction

Accurate values for daily inhalation rates in humans are required for health risk assessment and management of air pollutants (Health Canada 1996; van Engelen and Prud'homme de Lodder 2007) especially for the young and aged, who are thought to be more susceptible than adults to the adverse health effects of airborne chemicals (Braun-Fahrländer *et al.* 1997; Tolbert *et al.* 2000; Liu *et al.* 2003; Yang *et al.* 2003).

Estimates of daily inhalation rates in humans have been greatly improved with the use of the energy expenditure approach of Layton (1993). This approach has been formulated in a basic equation comprising the following terms (Equation 1): *E* (mean energy expenditure required for a given activity level expressed as kcal/min), *H* (oxygen uptake factor expressed as L of oxygen consumed/kcal expended), and VQ (ventilatory equivalent ratio of the minute ventilation rate (VE) to the oxygen consumption rate (VO_2), unitless). Nevertheless, the procedures developed by Layton (1993) to estimate *E* values are not free from biases and were showed to generate errors of daily inhalation estimates ranging from–36% to +60% (Brochu *et al.* 2006c). The difficulty in achieving accurate estimations of *E* values has been addressed by Brochu *et al.* (2006a, b) with the use of total daily energy expenditures (TDEE) that are measured from the doubly labeled

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Abbreviations

α	data for the aggregate daytime activities of subjects
β	data for subjects under resting conditions
BEE	basal energy expenditure (BMR expressed on a 24-h basis) BMI body mass index
BMR	basal metabolic rate (punctual measurement)
BSA	body surface area
BTPS	body temperature pressure saturation
DLW	doubly labeled water
E	minute energy expenditure rate
ECG	stored daily energy cost for growth
H	oxygen uptake factor, volume of oxygen (at STPD) consumed to produce 1 kcal of energy expended
RER	VCO_2/VO_2 ratio, more properly known as the respiratory exchange ratio
Sld	sleep duration
SMR	sleeping metabolic rate
STPD	standard temperature and pressure, dry air
TDEE	total daily energy expenditure
VCO_2	carbon dioxide production rate
VE	minute ventilation rate
VO_2	oxygen consumption rate (also known as the oxygen uptake)
VQ	ventilatory equivalent for VO_2 (VE at BTPS/VO_2 at STPD)

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water (DLW) method (Bluck 2008). Values for TDEE systematically encompass voluntary and involuntary energy expended by humans during real-life situations in their normal surroundings each minute of the day, 24 h per day, on a daily basis for 7–21 days (IDECG 1990).

The precise values of the two other parameters in the equation of Layton (i.e. *H* and VQ) are still a matter for discussion. A postprandial *H* value of 0.21 L of O_2/kcal has been first calculated for Americans by Layton (1993) and later confirmed for Canadians by Brochu *et al.* (2006a). However, a critical analysis of possible fluctuations in the postprandial *H* value as a function of age, sex, and typical dietary intakes in various countries has not been performed. Moreover, the variation of *H* values during nighttime sleep in fasting subjects has never been taken into account in the calculation process of daily inhalation rates. Similarly, VQ values have been shown to vary from 34.2 to 36.8 in pregnant and lactating women in Brochu *et al.* (2006b) compared with the constant value of 27 reported in Layton (1993). However, the accurate variation of VQ values in non-gestational and lactating individuals as a function of age has not yet been reliably characterized.

The present article is therefore intended to improve the methodology developed previously by Brochu *et al.* (2006a–c) for a scientifically sound determination of daily inhalation rates in free-living individuals based on DLW measurements. The overall approach involved the determination and integration of the means and standard deviations for *E*, *H*, and VQ for nighttime sleep (fasting phase) and daytime activities (postprandial phase) into the calculation process of physiological daily inhalation rates in normal-weight individuals.

Methodology

Study design

Means and standard deviations (SD) for *H* and VQ were determined initially and then used subsequently in the second part, with those of *E* and sleep durations (Sld), for the calculation of the physiological daily inhalation rates. Data for athletes and explorers were excluded from the calculation process of the latter values. Daily inhalation values were expressed as absolute values (m^3/day), as well as relative values to the body weight (m^3/kg-day) and body surface area (BSA; m^3/kg-m^2). Normal-weight individuals were defined according to the following body mass index (BMI) cutoffs: from the 3rd to 97th percentiles for children under 3 years old, the 85th percentile or below for children aged 3–19 years, and from 18.5 to 24.5 kg/m^2 for adults over 19 up to 96 years (IOM 2002). Infants, toddlers, children, and teenagers are hereafter collectively referred to children.

Values for *E* were determined by using individual DLW measurements taken from the database reported in IOM (2002) for healthy normal-weight males and females aged 2.6–96 years ($n = 1235$). These values, which are systematically measured with the DLW method, include subject-specific information on body weight, height, BMI value, basal energy expenditure (BEE), and TDEE values. Values for BEE were measured by indirect calorimetry (Ferrannini 1988; Bursztein *et al.* 1989), whereas those for TDEE were obtained by mass spectrometric monitoring of disappearance rates of oral doses of water isotopes usually monitored in the urine (IDECG 1990). Values for *E* during nighttime sleep were calculated by using BEE values. Those during the aggregate daytime activities are the result of subtracting BEE from TDEE values.

An exhaustive compilation and a critical analysis of published data in healthy subjects were performed in order to select appropriate parameters for the determination of *H* values during postprandial and fasting phases (i.e. typical diets found in various countries, respiratory gas-exchange measurements of oxygen and carbon dioxide) and VQ values under resting conditions and for the aggregate daytime activities (i.e. simultaneous measurements of minute ventilation and VO_2) (appendix).

Food recall surveys (i.e. retrospective method) or weighed dietary records (i.e. prospective method using household measures or collection of duplicate diets) are used to describe dietary intakes in subjects (Torun *et al.* 1996). Experimental procedures used for measurements of VO_2, carbon dioxide production (VCO_2), and VE are specified in each publication. However, VO_2 and VCO_2 values are often measured using paramagnetic O_2 and infrared CO_2 analyzers, respectively (Skoog *et al.* 2006). Values for VE are generally measured by spirometry and sometime by

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pneumotacography (Mason *et al.* 2005). Sld are recorded day-by-day on questionnaires by survey respondents for extensive periods of time (usually longer than a year) including complementary data, as those regarding work conditions, physical activities, diets, as well as health and socioeconomic variables (e.g. Bjorvatn *et al.* 2007).

$VO_2\beta$ and $VO_2\alpha$: criteria for data selection for H and VQ calculations

Published sets of measurements for VE, VO_2, and VCO_2, VO_2 values measured in healthy subjects at rest or while performing various activities at about the sea level, when breathing an oxygen concentration of 21%, were ranked per age groups. Then, only those measured in subjects with experimental VO_2 demands within the span of VO_2 values for resting conditions (referred to as β) or the aggregate daytime activities (referred to as α) were included in the present study. Values for $VO_2\beta$ and $VO_2\alpha$ were calculated by using BEE and TDEE values reported in the database of the IOM (2002) for healthy normal-weight individuals (age = 2.6 months–96 years; $n = 1235$). According to Layton (1993), VE (L/min) is expressed as a function of H (L of O_2/kcal), E (kcal/min), and VQ (i.e. VE/VO_2 ratio, unitless) values as follows:

$$\mathrm{VE} = E \times H \times \mathrm{VQ} \tag{1}$$

Hence,

$$\mathrm{VO_2} = E \times H \tag{2}$$

where H is the volume of oxygen consumed at standard temperature and pressure, dry air (STPD) to produce 1 kcal of energy expended, and VQ is the ratio of the VE value at body temperature and saturated with water vapor (BTPS) to the VO_2 value at STPD.

Therefore, values for minute energy expenditure rates (Eβ and Eα in kcal/min) as well as $VO_2\beta$ and $VO_2\alpha$ (L/min) were expressed in terms of BEE and TDEE values (kcal/day) as well as the daily energy costs for growth (ECG, in kcal/day) and Sld (in h/day) by using the following equations:

$$\mathrm{E}\beta = \left[\frac{\mathrm{BEE} + \mathrm{ECG}}{1440}\right] \tag{3}$$

$$\mathrm{E}\alpha = \left[\frac{\mathrm{TDEE} - \mathrm{BEE}}{(24 - \mathrm{Sld}) \times 60}\right] + \left[\frac{\mathrm{BEE} + \mathrm{ECG}}{1440}\right] \tag{4}$$

$$\mathrm{VO_2}\beta = \left[\frac{\mathrm{BEE} + \mathrm{ECG}}{1440}\right] \times H \tag{5}$$

$$\mathrm{VO_2}\alpha = \left[\frac{(\mathrm{TDEE} - \mathrm{BEE})}{(24 - \mathrm{Sld}) \times 60} + \frac{(\mathrm{BEE} + \mathrm{ECG})}{1440}\right] \times H \tag{6}$$

where 1440 and 60 are the conversion factors from days to minutes and hours to minutes, respectively, and 24 is the number of hours in a day.

Values for ECG were added to BEE values in order to take into account the energy demands required during the growth process from birth up to 18 years of age for females and 24 years old for males (Brochu *et al.* 2006a). The BEE value corresponds to the basal metabolic rate (BMR) expressed during a 24-h period. The BMR value is defined as the sum of the total energy expenditure required to maintain the minimal tissue cellular activity in order to sustain vital functions, notably blood circulation, respiration, gastrointestinal, and renal processes (Guyton 1991). BMR values are measured under standard conditions in a comfortably warm room, with subject lying at complete rest in thermoneutral conditions and having fasted for 12–13 h. Respiratory gas-exchange rates are measured for subjects 40 min immediately after waking (e.g. Butte *et al.* 2004). The postprandial H value of 0.21 L of O_2/kcal used by Layton (1993) and Brochu *et al.* (2006a–c) is in accordance with that calculated in the present study (0.207 L of O_2/kcal) by using VO_2 and BMR values per unit of organ weight established by Malcom and Hollyday (1971). Values for VO_2 per unit of tissue weight (3.7 to 123.8 L of O_2/kg-day) for brain, liver, heart, kidneys, and muscles reported in Malcom and Hollyday (1971) for adults correspond to a mean H value of 0.207 L of O_2/kcal for these five organs when divided by their respective BMR (17.6–606 kcal/kg of organ per day). Consequently, a H value of 0.21 L of O_2/kcal was used for the calculation of the lower and upper limits of $VO_2\beta$ and $VO_2\alpha$ for the different age groups in this study (Tables 1 and 2).

H values

Variations of the postprandial H value (referred to as H_P value) as a function of age, sex, and country were calculated based on typical dietary intake contributions found in 17 countries. This is done by taking into account absorption rates of ingested protein, fat, and carbohydrates (92%, 95%, and 98%, respectively) through the gastrointestinal tract (Guyton 1991) and considering that the oxidation of 1 g each of these nutrients consumes 0.97, 0.83, and 2.0 L of O_2 and yields 4.5, 9.5, and 4.2 kcal of energy, respectively (McLean and Tobin 1987; Layton 1993; Brochu *et al.* 2006a). Values for H_P and H for fasting subjects (referred to as H_F value) were also calculated by using values for VO_2 and VCO_2, or alternatively using VO_2 and respiratory exchange ratios (i.e. VCO_2/VO_2, known as the RER value) simultaneously measured by indirect calorimetry at STPD in the same subjects. Then, values for VO_2 and VCO_2 (L/min) were converted into minute energy expenditure rate (E, kcal/min) and H (L/kcal) by using the following equations (Weir 1949):

$$E = 3.941 \times \mathrm{VO_2} + 1.106 \times \mathrm{VCO_2} \tag{7}$$

$$H = \mathrm{VO_2} \times (3.941 \times \mathrm{VO_2} + 1.106 \times \mathrm{VCO_2})^{-1} \tag{8}$$

The combustion of carbohydrates, protein, and fat from ingested food requires 0.199, 0.212, and 0.221 L of O_2 per kcal of energy expended, respectively (McLean and

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Table 1. Anthropometric, energetic measurements, and oxygen consumption rates in healthy normal-weight males and females aged 2.6 months to <10 years.

Gender and age group (years)	n	Body weight (kg)[a]		Body surface area (m^2)		Energetic measurement (kcal/day)						Oxygen consumption rate (L/min)			
						BEE[b]		ECG[c]		TDEE[d]		$VO_2\beta$[e]		$VO_2\alpha$[e]	
		Mean ± SD	D	Mean ± SD	D	Mean ± SD	D	Mean ± SD	D	Mean ± SD	D	Min	Max	Min	Max
Males															
0.22 to <0.5	28	6.6 ± 1.0	L	0.34 ± 0.03	L	387 ± 64	L	121 ± 42	L	492 ± 125	L	0.06	0.09	0.06	0.19
0.5 to <1	37	8.8 ± 1.1	L	0.42 ± 0.03	L	532 ± 63	N	40 ± 9	L	722 ± 123	L	0.07	0.10	0.08	0.24
1 to <2	34	10.7 ± 1.1	N	0.49 ± 0.04	N	668 ± 71	N	22 ± 4	L	890 ± 145	L	0.07	0.12	0.11	0.28
2 to <5	25	15.3 ± 3.4	N	0.64 ± 0.10	N	846 ± 153	N	17 ± 4	L	1176 ± 274	L	0.09	0.16	0.13	0.35
5 to <7	96	19.8 ± 2.1	L	0.79 ± 0.06	L	1012 ± 91	N	41 ± 6	L	1398 ± 192	L	0.12	0.20	0.18	0.45
7 to <10	28	26.8 ± 4.2	L	0.98 ± 0.10	L	1129 ± 116	N	51 ± 10	L	1722 ± 322	L	0.13	0.21	0.18	0.55
Females															
0.22 to <0.5	49	6.6 ± 0.9	L	0.34 ± 0.03	L	374 ± 53	L	117 ± 42	L	471 ± 102	L	0.06	0.09	0.07	0.20
0.5 to <1	63	8.5 ± 1.0	L	0.41 ± 0.03	L	506 ± 67	L	38 ± 7	L	661 ± 121	N	0.06	0.10	0.07	0.24
1 to <2	61	10.6 ± 1.4	L	0.49 ± 0.04	L	630 ± 85	L	18 ± 3	L	844 ± 160	N	0.07	0.13	0.09	0.28
2 to <5	36	14.4 ± 3.0	L	0.62 ± 0.09	L	776 ± 132	N	19 ± 4	L	1083 ± 219	L	0.08	0.16	0.11	0.34
5 to <7	102	19.7 ± 2.3	L	0.79 ± 0.06	L	943 ± 75	N	34 ± 5	L	1332 ± 184	L	0.12	0.17	0.16	0.39
7 to <10	140	27.3 ± 3.6	L	0.99 ± 0.08	L	1079 ± 86	N	42 ± 7	L	1660 ± 265	L	0.13	0.20	0.19	0.51

N = normal; L = lognormal. n = number of individuals; SD = standard deviation.

[a]Normal-weight for children aged 2.6 months to <3 years with body mass index (BMIs) between the 3rd and the 97th percentiles and those aged 4 to <10 years with BMIs corresponding to the 85th percentile or below (IOM 2002).

[b]BEE = basal energy expenditure (i.e. basal metabolic rate expressed on a 24-h basis) measured by indirect calorimetry (IOM 2002).

[c]ECG = stored daily energy cost for growth (Brochu et al. 2006a).

[d]TDEE = total daily energy expenditure. TDEEs were based on ^2H_2O and $H_2{}^{18}O$ disappearance rates from urine monitored by gas–isotope ratio mass spectrometry during 7- to 21-day periods for free-living individuals (IOM 2002).

[e]$VO_2\beta$ and $VO_2\alpha$ = oxygen consumption rates for individuals at rest and during aggregate daytime activities, respectively, used for the selection of data for the calculation of H and VQ values. D = best fit distribution (i.e. lognormal or normal) according to the Anderson–Darling goodness-of-fit test performed on individual data for each age group.

Tobin 1987). During the fasting phase, 0.198, 0.200, 0.210, 0.211, and 0.214 L of O_2/kcal are required for the combustion of glycogen, glucose, 3-hydroxybutyric acid, acetoacetic acid, and triacylglycerol, respectively (Elia 1997). Consequently, a minimum of 0.199 L of O_2/kcal and maximum of 0.221 L of O_2/kcal for H_P values (McLean and Tobin 1987), as well as minimal and maximal H_F values of 0.198 and 0.214 L of O_2/kcal, respectively (Elia 1997), were used into the calculation process of physiological daily inhalation rates.

VQ values

Values for VQ were calculated by dividing VE by VO_2 values simultaneously measured for the same subjects at BTPS and STPD, respectively. Voluntary and involuntary activities during daytime are performed by individuals in the sitting or standing position. Therefore, VQα values were calculated exclusively by using published VEα and $VO_2\alpha$ measured while subjects were in the upright position. The data for subjects in the supine position were insufficient to calculated VQβ values. However, only slightly higher energy expenditure is required when subjects, during resting conditions, change from a supine to an upright position, which consequently increase VO_2, VCO_2, VE values by about the same extent (e.g. Donevan *et al.* 1962; Damato *et al.* 1966). Conversely, lower BMR values observed in normal-weight subjects during profound sleep (e.g. Ravussin *et al.* 1985; Garby *et al.* 1987) slightly reduce VE and VO_2 demands as well (e.g. Colrain *et al.* 1987). These fluctuations of VO_2 demands combined with the change of VE and VO_2 values always remain within the span of $VO_2\beta$. Therefore, VQβ values were calculated by using sets of VEβ and $VO_2\beta$ values measured in subjects in the upright position. Such VQβ values can be used to characterize VQ values for subjects during resting conditions in the upright or supine position as well as during nighttime sleep.

Published sets of VE and VO_2 values were found for individuals aged <1 year and for those from 4 to 91 years in the supine and upright positions, respectively. No data were available for children from 1 to <4 years of age. Thus, VQ values for the latter aged group were assumed to be the same as those for children aged 1 to <10 years. Mean VQβ values of 30.2 ± 7.6 and 30.8 ± 0.9 calculated for nonsedated children aged 2 h to 1.4 months (Cook *et al.* 1955; Stahlman and Meece 1957; Nelson *et al.* 1962; n = 131) and 4 to <10 years, respectively (Robinson 1938; Inbar *et al.* 1981; n = 35), are within the same order of magnitude, and both appear to be slightly higher than the value of 27.0 ± 4.3 based on data reported in Lees *et al.* (1967) for sedated children aged 0.5–8.5 months (n = 26). Therefore, the former value (i.e. 30.2 ± 7.6) was used to characterize VQβ in children aged 2.6 months to <1 year rather than the latter (i.e. 27.0 ± 4.3). The VQα value for children aged <1 year old was assumed to be the same as the VQβ value since such children have limited

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Table 2. Anthropometric, energetic measurements, and oxygen consumption rates in healthy normal-weight males and females aged 10–96 years.

Gender and age group (years)	n	Body weight (kg)[a]		Body surface area (m^2)		Energetic measurement (kcal/day)						Oxygen consumption rate (L/min)			
						BEE[b]		ECG[c]		TDEE[d]		$VO_2\beta$[e]		$VO_2\alpha$[e]	
		Mean ± SD	D	Mean ± SD	D	Mean ± SD	D	Mean ± SD	D	Mean ± SD	D	Min	Max	Min	Max
Males															
10 to <16.5	26	43.5 ± 11.6	L	1.36 ± 0.24	L	1474 ± 287	L	89 ± 36	L	2488 ± 635	L	0.15	0.32	0.28	0.81
16.5 to <25	25	70.5 ± 6.1	N	1.87 ± 0.10	L	1737 ± 156	N	78 ± 41	N	3132 ± 527	N	0.22	0.31	0.35	0.72
25 to <35	46	71.3 ± 6.8	N	1.88 ± 0.12	N	1740 ± 168	L	0 ± 0		3012 ± 467	L	0.21	0.30	0.36	0.79
35 to <45	34	70.3 ± 6.5	N	1.86 ± 0.11	N	1625 ± 148	L	0 ± 0		3008 ± 386	L	0.19	0.30	0.40	0.66
45 to <65	17	72.3 ± 7.9	N	1.88 ± 0.14	N	1681 ± 309	L	0 ± 0		2697 ± 492	L	0.20	0.36	0.34	0.66
65 to ≤96	50	68.9 ± 6.7	L	1.82 ± 0.11	L	1480 ± 187	L	0 ± 0		2286 ± 437	L	0.17	0.30	0.22	0.60
Females															
10 to <16.5	95	45.2 ± 9.1	L	1.39 ± 0.18	N	1278 ± 150	L	82 ± 25	L	2143 ± 457	L	0.15	0.27	0.20	0.73
16.5 to <25	30	60.6 ± 5.6	L	1.68 ± 0.10	N	1385 ± 141	N	17 ± 39	N	2523 ± 294	N	0.15	0.24	0.30	0.61
25 to <35	88	58.7 ± 6.7	L	1.64 ± 0.12	L	1346 ± 154	N	0 ± 0		2387 ± 373	L	0.15	0.26	0.24	0.68
35 to <45	29	58.9 ± 4.8	N	1.64 ± 0.08	N	1320 ± 114	N	0 ± 0		2441 ± 334	L	0.15	0.22	0.31	0.57
45 to <65	51	58.7 ± 4.9	N	1.63 ± 0.09	N	1211 ± 139	L	0 ± 0		2128 ± 338	N	0.14	0.24	0.23	0.57
65 to ≤96	45	57.2 ± 7.3	L	1.60 ± 0.13	L	1217 ± 152	L	0 ± 0		1729 ± 383	L	0.15	0.25	0.16	0.52

N = normal; L = lognormal. n = number of individuals; SD = standard deviation.

[a]Normal-weight for children aged 10–19 years with body mass index (BMI) corresponding to 85th percentile or below and adults aged 20–96 years with BMIs between 18.5 and 25 kg/m^2 (IOM 2002).

[b]BEE = basal energy expenditure (i.e. basal metabolic rate expressed on a 24-h basis) measured by indirect calorimetry (IOM 2002).

[c]ECG = stored daily energy cost for growth (Brochu et al. 2006a).

[d]TDEE = total daily energy expenditure. TDEEs were based on ^2H_2O and $H_2{}^{18}O$ disappearance rates from urine monitored by gas–isotope ratio mass spectrometry during 7- to 21-day periods for free-living individuals (IOM 2002).

[e]$VO_2\beta$ and $VO_2\alpha$ = oxygen consumption rates for individuals at rest and during aggregate daytime activities, respectively, used for the selection of data for the calculation of H and VQ values. D = best fit distribution (i.e. lognormal or normal) according to the Anderson–Darling goodness-of-fit test performed on individual data for each age group.

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physical capacity and opportunities for doing a great deal of demanding exercises (Polgar and Weng 1979; Guyton 1991). No published VE and VO_2 were found for children from 1 to <10 years of age for VO_2 demands within the span of $VO_2\alpha$. Values for VQβ and VQα for the latter age group were assumed to be the same (i.e. 30.8 ± 0.9), considering the small difference found between VQβ (27.7 ± 3.4, n = 145) and VQα (29.9 ± 4.2, n = 166) values in older children aged 10 to <16.5 years (Table 3).

Accuracy of energetic measurements

The accuracy of E, as well as the BEE values based on the gas exchange of VO_2 and VCO_2 monitored by indirect calorimetry and calculated with the use of the Weir equation (Equation 7), has been shown to vary from +1% to +2% compared with values measured by steady-state direct calorimetry in a sealed chamber (Turel and Alexander 1964). Consequently, H_P and H_F values calculated based on the Equation 8 are affected by an error ranging from–2% to–1%. During DLW measurements, subjects are advised not to change their usual sources of ingested water for the entire duration of the study. Changing water sources during the isotope elimination period has been found to lead to an increase in the mean error of TDEE values by–8.7% in infants and +5.3% in soldiers (Delany *et al.* 1988; Jones *et al.* 1988). However, the mean accuracy of TDEE values from DLW method has been validated against other methods, including metabolic chambers as varying from –1.0% to +3.3% when the sources of tap water were not modified during the entire period (IDECG 1990). This range of errors also affects the accuracy of ECG values (Brochu *et al.* 2006a). Therefore, the combined effects of simultaneous minimal and maximal mean errors associated with H_P, H_F (i.e.–2% to–1%), BEE (i.e. +1% to +2%), TDEE, and ECG values (i.e.–1.0% to +3.3%) on the order of magnitude of physiological daily inhalation rates were determined in the present study.

Physiological daily inhalation rates

Tidal volumes, breathing frequency rates, VE and VO_2 values (e.g. Tabachnik *et al.* 1981; Colrain *et al.* 1987; Hudgel *et al.* 1993; Morrell *et al.* 1995), systolic and diastolic blood pressures, and heart rates have all been shown to be lower in sleeping subjects compared with their awaken counterparts (e.g. Carrington *et al.* 2005; Zaregarizi *et al.* 2007). These findings are in accordance with the reduction of BMR values during sleep. Based on heat production measured in sleeping subjects by direct calorimetry, the sleeping metabolic rates (SMR) were calculated to be 0.960 ± 0.023 times the BMR values in normal-weight (n = 86) individuals (Benedict and Carpenter 1910; Buskirk *et al.* 1960; Bessard *et al.* 1983; Schutz *et al.* 1984; Shapiro *et al.* 1984; Ravussin *et al.* 1985; Garby *et al.* 1987). This correcting factor (referred to as F_{sleep}) affecting BEE values as well as the minimal and maximal F_{sleep} values of 0.870 and 1.039 were integrated into the following

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Table 3. Ventilatory equivalents for healthy individuals aged 2 h to 96 years at rest and during aggregate daytime activities.

Age groups for both genders (years)	Ventilatory equivalents (L of air inhaled/L of O_2 consumed)[a]																
	During resting conditions[b] (VQβ)				During the aggregate daytime activities[b] (VQα)				Below the anaerobic threshold				During anaerobiosis			
											VO_2[c]				VO_2[c]	
	n	Mean ± SD	Min	Max	*n*	Mean ± SD	Min	Max	*n*	Mean ± SD	Min	Max	*n*	Mean ± SD	Min	Max
<1	131	30.2 ± 7.6	16.7	60.8		Same values as those for VQβ				Not applicable				Not applicable		
1 to <10	35	30.8 ± 0.9	25.4	46.6		Same values as those for VQβ			27	26.6 ± 0.9	0.54	0.70	88	36.9 ± 5.2	0.86	2.62
10 to <16.5	145	27.7 ± 3.4	17.1	39.4	166	29.9 ± 4.2	18.9	49.2	23	30.0 ± 0.4	0.76	0.92	1282	37.6 ± 2.1	1.50	4.47
16.5 to <25	114	27.4 ± 4.8	14.4	47.4	85	32.2 ± 6.1	21.0	100.5	459	26.9 ± 2.0	0.72	1.81	818	35.3 ± 2.3	3.00	5.63
25 to <35	133	32.2 ± 3.1	18.0	64.0	318	32.6 ± 4.7	15.7	84.6	390	29.8 ± 2.8	0.80	1.78	535	33.6 ± 1.5	3.01	5.18
35 to <45	60	30.6 ± 2.2	22.1	48.0	47	33.1 ± 8.6	15.3	91.5	205	26.1 ± 1.9	0.75	1.75	125	37.7 ± 1.5	3.14	4.23
45 to ≤96	38	30.6 ± 2.6	22.3	40.8	59	33.7 ± 7.2	16.0	76.5	89	28.7 ± 2.1	0.77	1.17	2736	35.7 ± 1.0	1.51	4.94

n = number of individuals; SD = standard deviation; Min = minimal value; Max = maximal value.
[a]VQ = ratio of the minute ventilation rate (VE in L/min at BTPS) to the oxygen uptake (VO_2 in L/min at STPD). The simultaneous VE and VO_2 measurements used for VQ calculations were taken from different studies, which are cited in the appendix.
[b]VO_2 values for VQβ and VQα vary from 0.06 to 0.36 and 0.06 to 0.81 L/min, respectively (Tables 1 and 2).
[c]Oxygen consumption rate (in L/min).

equation in order to determine the SMR values (in kcal/min) for subjects during sleep in the supine position:

$$\mathrm{SMR} = \left[\frac{\left(\mathrm{BEE} \times F_{\mathrm{sleep}}\right) + \mathrm{ECG}}{1440} \right] \tag{9}$$

Values for physiological daily inhalation rates (m^3/day) were then calculated by using the following expression:

$$\mathrm{PDIR} = \left[\begin{array}{l} (\mathrm{SMR} \times H_{\mathrm{F}} \times \mathrm{VQ}\beta \times \mathrm{Sld}) + \\ (\mathrm{E}\alpha \times H_{\mathrm{P}} \times \mathrm{VQ}\alpha) \times (24 - \mathrm{Sld}) \end{array} \right] \times 0.06 \tag{10}$$

where 0.060 is the combined conversion factor from hours to minutes and liters (L) to cubic meters (m^3).

Values for physiological daily inhalation rates expressed per unit of BSA were determined by using the BSA values calculated on the basis of height (cm) and weight (kg) values as follows (Mosteller 1987):

$$\mathrm{BSA} = \left[\frac{\mathrm{height} \times \mathrm{weight}}{3600} \right]^{0.5} \tag{11}$$

Sleep durations

Sld from the literature were used in this study regardless of the under-, normal-, overweight, and obese proportions of individuals in the different cohorts. However, several publications suggest that overweight and obese children and adults have shorter night sleep compared with their normal-weight counterparts (Taheri *et al.* 2004; Cizza *et al.* 2005; Gangwisch *et al.* 2005; Vorona *et al.* 2005; Beebe *et al.* 2006; Kohatsu *et al.* 2006; Patel *et al.* 2006; Taheri 2006; Bjorvatn *et al.* 2007; Seicean *et al.* 2007). On the contrary, some publications challenge this view (Koçoglu *et al.* 2003; Gibson *et al.* 2004; Hasler *et al.* 2004; Eisenmann *et al.* 2006). To dispel the influence of this ambiguity on inhalation values, two sets of daily inhalation rates were calculated and compared.

A first set of physiological daily inhalation rates was calculated by using the Sld reported in Bernstein *et al.* (2001) and Eisenmann *et al.* (2006) for small cohorts of subjects composed of known proportions of normal-weight, overweight, and obese individuals (i.e. 10.9% of boys and 13.6% of girls aged 7.5 to 10.9 years, 10.7% of males and 11.9% of females aged 11–16.5 years were overweight or obese; in adults aged 35–74 years, 45% of males and 24% of females were overweight, 9% of males and 13% of females were obese). This set of values was compared with a second set of inhalation rates that was calculated when Sld for percentages of overweight/obese individuals in both cohorts were decreased by 25%. This process of calculation corresponds to the worst case scenario based on data reported in the literature. Sld for 60% of overweight/obese children were decreased by 25% based on published values that indicate that 13.5–57.6% of overweight/obese children aged 7.5–16.5 years ($n = 6426$) have sleep deprivation varying from 13.1% to 21.9% (Eisenmann *et al.* 2006; Seicean *et al.* 2007). Sld for 35% of overweight adults and 55% of their obese counterparts were decreased by 25% considering the fact that 27.8–35.1% of overweight adults and 29.3% to 53.1% of their obese counterparts ($n = 96{,}570$) aged 32–86 years (Gangwisch *et al.* 2005; Kohatsu *et al.* 2006; Patel *et al.* 2006; Bjorvatn *et al.* 2007) have Sld 14.3–25.4% and 16.4–26.2%, respectively, shorter than the healthy baseline of 7 h per night (Kripke *et al.* 2002; Patel *et al.* 2004; Cizza *et al.* 2005; Gangwisch *et al.* 2005; Seicean *et al.* 2007).

Statistical analysis

Means, SD values, and distribution percentiles were calculated for all values, which were grouped by age with >30 subjects per group in order to optimize the probability of achieving a normal distribution for each age group, as formally recommended according to the central limit theorem (Feller 1945; Trotter 1959; Rice 1995). Monte

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Carlo simulations were used in order to take into account SD values into mean calculations and different physiological equations. Each calculation process was based on random sampling involving 10,000 iterations. Log normal distributions of Sld were used into the calculation process of physiological daily inhalation rates based on data reported in Knutson and Lauderdale (2007) and Seicean *et al.* (2007). Distributions of other parameters were defined to be either lognormal or normal according the Anderson–Darling goodness-of-fit tests performed on individual data (Tables 1–4). The same statistical test was used to define the best fit distributions of the resulting physiological daily inhalation rates per age group. The number of individual observations in fasting subjects reported in Gibney *et al.* (2003) and Shepherd *et al.* (2007) was insufficient ($n=8$) for the use of the Anderson–Darling test. Therefore, individual H_P ($n=102$) values for subjects in the supine position were statically tested in order to characterize the distribution type for the H_F value during nighttime sleep.

Results

Mean and SD values for body weights, BSA, BEE, ECG, and TDEE as well as lower and upper limits of $VO_2\beta$ and $VO_2\alpha$ are presented in Tables 1 and 2, while those for Sld are reported in Table 5. Mean H_P values resulting from nutrient intakes in different countries are given in Tables 6–8. Those for mean and SD values and distribution percentiles of VQβ and VQα values as well as mean and SD values for VQ ratios below the anaerobic threshold and during anaerobiosis are presented in Table 3. Means and distribution percentiles of physiological daily inhalation rates in normal-weight males and females aged 2.6 months to 96 years are given in Tables 9 and 10 respectively. Mean values for daily inhalation rates as a function of age are presented in Figures 1–3.

Results of Anderson–Darling goodness-of-fit tests on anthropometric and energetic values are reported in Tables 1 and 2, while those on respiratory parameters are given in Table 4. Finally, physiological daily inhalation rates for all age groups in m^3/day, m^3/kg-day, as well as m^3/m^2-day better fit with lognormal distributions except for those in m^3/ day for girls aged 1 to <2 years, which better fit with a normal distribution (data not shown in tables).

Values for H_P based on dietary intakes were found to vary between 0.203 and 0.208 L of O_2/kcal in 17 countries (Table 6), albeit North-American values range from 0.206 to 0.208 L of O_2/kcal. H_P values for the Canadian population range from 0.205 to 0.207 L of O_2/kcal for in term infants after birth and remain relatively constant

Table 4. Distribution type of parameters used in the calculation process of ventilatory equivalents, oxygen uptake factors, and physiological daily inhalation rates.

Parameter	Acronym[a]	n	Age (years)	Distribution
	$VO_2\beta$	337[b]	0.22 to 96	Normal
Oxygen consumption rate (L/min)	$VO_2\alpha$	307[b]	1 to 96	Lognormal
	$VO_{2\text{Sub-anaerobiosis}}$	682[b]	1 to 96	Lognormal
	$VO_{2\text{Anaerobiosis}}$	296[b]	1 to 96	Lognormal
Carbon dioxide production (L/min)	$VCO_2\beta$	162[b]	0.22 to 96	Normal
	$VCO_2\alpha$	117[b]	1 to 96	Lognormal
	VEβ	131[b]	0.22 to <1	Normal
Minute ventilation rate (L/min)	VEβ	49[b]	1 to 96	Lognormal
	VEα	141[b]	1 to 96	Lognormal
	$VE_{\text{Sub-anaerobiosis}}$	682[b]	1 to 96	Lognormal
	$VE_{\text{Anaerobiosis}}$	296[b]	1 to 96	Lognormal
Respiratory exchange ratio (unitless)	RERβ[c]	162[b]	1 to 96	Lognormal
	RERα[c]	117[b]	1 to 96	Lognormal
Ventilatory equivalent ratio (unitless)	VQβ[d]	280[b]	0.22 to 96	Lognormal
	VQα[d]	141[b]	1 to 96	Lognormal
Oxygen uptake factor (L of O_2/kcal)	H_F[e]	102[b]	0.22 to 96	Normal
	H_P[f]	229[b]	0.22 to 96	Lognormal
Sleep duration (h/day)	Sld	2055[g]	0.22 to 96	Lognormal

n = number of individual data on which the best fit distribution (i.e. lognormal or normal) has been defined.
[a]β = for subjects at rest. α = during the aggregate daytime activities of subjects.
[b]Best fit distribution (i.e. lognormal or normal) according to the Anderson–Darling goodness-of-fit test performed on individual data taken from studies cited in the appendix and Johnson et al. (1960), Reeves et al. (1961), Åstrand et al. (1964), Frick and Somer (1964), Emirgil et al. (1967), Hermansen et al. (1970), Jones et al. (1970), Pernow and Saltin (1971), and Capderou et al. (1997).
[c]RER = VCO_2/VO_2 ratio.
[d]VQ = VE/VO_2 ratio.
[e]During fasting phase.
[f]During postprandial phase.
[g]Lognormal distribution based on data reported in Knutson and Lauderdale (2007) and Seicean et al. (2007).

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Table 5. Sleep duration in healthy individuals aged 2.6 months to 96 years.

Gender and age group (years)	Sleep duration (h/day) n	Mean ± SD
For both genders		
0.22 to <0.5	456[a]	14.2 ± 1.9
0.5 to <1	916[a]	13.9 ± 1.0
1 to <2	912[a]	13.4 ± 0.8
2 to <5	1361[a]	11.9 ± 0.6
5 to <7	900[a]	10.8 ± 0.5
Males		
7 to <10	919[b]	9.9 ± 1.2
10 to <16.5	2284[b]	9.2 ± 0.8
16.5 to <25	552[c]	8.0 ± 1.2
25 to <35	127[c]	8.0 ± 2.0
35 to <45	670[d]	7.2 ± 0.7
45 to <65	1192[d]	8.0 ± 0.5
65 to ≤96	366[d]	8.8 ± 0.7
Females		
7 to <10	953[b]	10.2 ± 1.0
10 to <16.5	2168[b]	9.3 ± 0.8
16.5 to <25	712[c]	8.5 ± 1.1
25 to <35	172[c]	8.4 ± 1.6
35 to <45	784[d]	8.1 ± 0.7
45 to <65	1196[d]	8.2 ± 0.5
65 to ≤96	376[d]	9.1 ± 0.7

[a]Iglowstein et al. (2003).
[b]Eisenmann et al. (2006).
[c]Adams (2006).
[d]Adams (2006) and Bernstein et al. (2001).

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(variation of values ≤0.5%) into advanced age (Table 7). Values for H_P were confirmed to almost always be identical between males and females of the same age living in the same country. Variations observed were consistently <0.4% (Table 8). Values of 0.206, 0.207 and 0.209 L of O_2/kcal were calculated for the 10th, 50th, and 90th percentiles based on Canadian nutrient intake contributions observed and compiled by Brault-Dubuc and Mongeau (1989) over a 10-year span ($n = 747$). H_P values were calculated to be 0.206, 0.207, 0.207 L of O_2/kcal for underweight ($n = 14$), normal-weight ($n = 25$), and obese adults ($n = 18$), respectively, based on typical German diet (Bosy-Westphal *et al.* 2004). H_P values for black ($n = 246$) and white Americans ($n = 703$), calculated in this study, based on their nutrient intakes (Morisson *et al.* 1980) vary by <0.5%.

Results of H_P and H_F values calculated based on simultaneous VO_2 and VCO_2 measurements are not shown in tables. Values for an H_F of 0.205 ± 0.003, 0.206 ± 0.003, and 0.207 ± 0.003 L of O_2/kcal for subjects at rest in a semi-recumbent (Müeller *et al.* 1989; $n = 5$), almost supine (Saltzman and Salzano 1971; $n = 20$) and supine position (Gibney *et al.* 2003; $n = 6$) were calculated with VO_2, E, and RER values varying from 0.225 ± 0.035 to 0.307 ± 0.044 L/min, 1.09 ± 0.05 to 1.47 ± 0.07 kcal/min, and 0.802 ± 0.057 to 0.858 ± 0.072, respectively. A mean H_F value of 0.205 ± 0.001 L of O_2/kcal was also calculated for adults aged 23–30 years ($n = 27$) performing exercise in the upright position below the anaerobic threshold (De Bock *et al.* 2005; VO_2 of 2.83 ± 0.05 L/min, VCO_2 of 2.37 ± 0.05 L/min, E of 13.41 ± 0.21 kcal/min, RER of 0.838 ± 0.023 with minimal and maximal values of 0.759 and 0.928, respectively). These results show that the level of exertions in fasting subjects (thus VO_2 demands at rest or during exercise below the anaerobic threshold), and their positions (i.e. upright or supine position) during measurements had a negligible effect on their H_F values (by <1%). Consequently, H_F and H_P values for nighttime sleep and the aggregate daytime activities, respectively, were calculated by using VO_2 and VCO_2 values measured in healthy subjects while performing activities with VO_2 demands that were within the entire span of $VO_2\beta$ and $VO_2\alpha$ values varying from 0.06 to 0.79 L/min (Tables 1 and 2) regardless of their positions during the experimental protocols. Values for H_F of 0.2057 ± 0.0018 L of O_2/kcal ($n = 31$) and H_P of 0.2059 ± 0.0019 L of O_2/kcal ($n = 1245$) were then calculated. The H_P value was calculated by using published data for individuals aged 2 h to 73 years ($n = 327$) in the supine position and 8.8–81 years ($n = 918$) in the upright position (Tenney and Miller 1956; Baker *et al.* 1957; Spurr *et al.* 1957; Emirgil *et al.* 1967; Pernow and Saltin 1971; Oren *et al.* 1981; Allen *et al.* 1984; Capderou *et al.* 1997; Treuth *et al.* 1998; Gisolf *et al.* 2003; Cade *et al.* 2004; Shiou-Liang *et al.* 2005; other references are underlined in the appendix). During the postprandial phase, VO_2, E, and RER values of 0.184 ± 0.011 L/min, 0.90 ± 0.04 kcal/min, and 0.866 ± 0.074, respectively, were calculated for individuals in the supine position, compared with a VO_2 of 0.291 ± 0.013 L/min, an E of 1.41 ± 0.05 kcal/min, and a RER of 0.817 ± 0.050 for subjects in the upright position.

The worst case scenario of decreased Sld in overweight/obese subjects has reduced the global physiological daily inhalation rates of entire cohorts of subjects by only 0.03% to 0.17% (data not shown in tables). Initial Sld of 9.9 ± 1.2 ($n = 919$), 9.2 ± 0.8 ($n = 2284$), 7.8 ± 0.3 h/day ($n = 1707$) in males and 10.2 ± 1.0 ($n = 953$), 9.3 ± 0.8 ($n = 2168$), 8.2 ± 0.4 h/day ($n = 1703$) in females have been published for subjects aged 7.5–10.9, 11–16.5, and 35–74 years, respectively (Bernstein *et al.* 2001; Eisenmann *et al.* 2006). Classified in the same order, initial Sld values of entire cohorts of subjects were decreased to 9.7 ± 1.1, 9.0 ± 0.8, 7.3 ± 0.3 h/day for males and 10.0 ± 0.9, 9.1 ± 0.8, 7.9 ± 0.3 h/day for females as a result of a 25% reduction in Sld for 60% of overweight/obese children and 35% of overweight as well as 55% of obese adults. Sld specifically for overweight/obese subjects aged 7.5–10.9, 11–16.5, and 35–74 years were decreased to 7.4 ± 0.8, 6.9 ± 0.6, 5.8 ± 0.3 h/day in males and 7.6 ± 0.7, 7.0 ± 0.6, 6.1 ± 0.3 h/day in females, respectively.

Lower and upper mean errors associated with H_P, H_F (i.e.–2% to–1%), BEE (i.e. +1% to +2%), TDEE, and ECG values (i.e.–1.0% to +3.3%) affect physiological daily inhalation rates by –2.0 to –1.0, –0.08 to –0.01, –1.0 to +3.4, and –0.2 to +0.7%, respectively. Simultaneous maximal mean errors associated with H_P, H_F values (–1%), BEE (+2%), ECG, and TDEE values (+3.3%) increase

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Table 6. Postprandial oxygen uptake factor resulting from daily nutrient intakes for all ages by country.

Age (years)	n	Nutrient intake contributions (%) Protein	Fat	COH[a]	Oxygen uptake factor[b] (L of O_2/kcal)	Country
1 to 9	1442	17.4	20.6	62.0	0.206	Australia[c]
<1 month to 65+	13,211	17.4	20.6	62.0	0.206	Canada[d]
24 to 74	1010	21.9	15.1	63.0	0.206	China[e]
1 to 24	3147	17.7	21.8	60.5	0.206	Finland[f,g]
3 to 65+	3003	16.7	38.1	45.3	0.208	France[h]
25 to 27	57	14.1	35.0	48.3	0.207	Germany[i]
8.9	116	9.2	22.0	68.0	0.204	Ghana[f]
2 to 8	101	18.5	23.2	58.2	0.206	Greece[j]
2 to 6	99	11.9	24.8	63.3	0.205	India[k]
9 and ≤60	1055	17.6	17.9	64.3	0.205	Italy[f,l]
40 to 50	351	19.4	15.1	65.5	0.205	Japan[m]
2 to 8; 50 to 69	1225	16.5	26.9	56.0	0.206	Sweden[j,n]
1.3 to 9	684	13.5	35.3	51.3	0.207	The Netherlands[f,o]
8.8	114	11.7	16.0	72.0	0.204	The Philippines[f]
0.5 to 1 2	2026	15.4	21.8	64.4	0.205	UK[p]
1 week to 75+	74,275	17.4	34.6	47.6	0.208	USA[l,q]
All ages	17,763	9.8	11.4	78.9	0.203	Vietnam[r]

[a]COH = Carbohydrate.
[b]H_P = postprandial oxygen uptake factor.
[c]Hitchcock et al. (1984) and Jenner et al. (1988).
[d]NC (1977), Leung et al. (1984), and Brault-Dubuc and Mongeau (1989).
[e]Woo et al. (1998).
[f]Knuiman et al. (1983).
[g]Räsänen et al. (1985), Räsänen et al. (1991), and Räsänen and Ylönen (1992).
[h]Razanamahefa et al. (2005).
[i]Bosy-Westphal et al. (2004).
[j]Neiderud et al. (1992).
[k]Narasinga et al. (1982).
[l]Freudenheim et al. (1993).
[m]Tokudome et al. (1998).
[n]Riboli et al. 1997.
[o]Hoffmans et al. (1986).
[p]Bransby and Fothergill (1954), Margarey and Boulton (1984), Nelson et al. (1990), Payne and Belton (1992), and Ruxton et al. (1996).
[q]Morisson et al. (1980), Butte and Calloway (1981), Reichman et al. (1981), DHHS (1983), Gross (1983), Butte et al. (1984), USDA (1984), Pao et al. (1985), Oliveria et al. (1992), Simons-Morton et al. (1997), and Bollella et al. (1999).
[r]Thang and Popkin (2004).

daily inhalation values by +2.3%. The inverse scenario is observed with simultaneous minimal mean errors for H_P, H_F (−2%), BEE (+1%), ECG, and TDEE (−1.0%) values affecting physiological daily inhalation rates by–3.0%. The use of SMR instead of BEE values (in Equation 10) has reduced daily inhalation values by only 0.6% to 1.8%. The use of the lowest H value of 0.203 L of O_2/kcal for Vietnamese (n = 17,763) and the highest value of 0.208 L of O_2/kcal for American (n = 74,275) during the postprandial phase (Table 6) could have affected the physiological daily inhalation rates by only −1.2% to −0.7% and +0.5% to +0.9%, respectively, compared with the inhalation values calculated in this study based on H_P value of 0.2059 L of O_2/kcal.

Discussion

All mean and almost all (98%) percentile values of physiological daily inhalation rates calculated in the present article (in m^3/day, m^3/kg-day, and m^3/m^2-day) are higher in males than in females, and are in accordance with Brochu *et al.* (2006a–c). As found in our previous studies, mean daily inhalation values expressed in m^3/kg-day follow a logarithmic pattern (Figure 2). Values drop rapidly with increasing age, from 16.5 to <25 years in females (R^2 = 0.94) and males (R^2 = 0.96). Then mean physiological daily inhalation rates continue to decrease slowly as age increases up to 65 to 96 years. Mean daily inhalation values in males (0.225 ± 0.059 m^3/kg-day) and females (0.202 ± 0.059 m^3/kg-day) aged 65–96 years are found to be 61% and 64% lower, respectively, than those for boys (0.572 ± 0.191 m^3/kg-day) and girls (0.563 ± 0.180 m^3/kg-day) 2.6 to <6 months old. When females and males age from 2.6 months to <16.5 years, body weights increase proportionally more (by 9.2- and 10.6-folds, respectively) than height does (by 2.7- and 2.8-folds, respectively). This results in a moderate increase of BSA values by 5.0- and 5.5-folds, respectively. Beyond these ages, very few changes appear for weight, height, and BSA values. This explains why the

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Table 7. Postprandial oxygen uptake factor resulting from daily nutrient intakes for both sexes as a function of age.

Age	n	Nutrient intake contributions (%) Protein	Fat	COH[a]	Oxygen uptake factor[b] (L of O_2/kcal)
Breast milk					
1 week[c]	60	18.7	26.3	55.1	0.207
2 weeks[c]	60	15.3	27.9	56.8	0.206
3 weeks[c]	60	13.0	28.4	58.5	0.206
4 weeks[c]	60	11.6	30.6	57.8	0.206
5 weeks[c]	60	11.0	30.4	58.6	0.206
1 month[d]	37	9.0	33.3	57.7	0.206
1 month[e]	10	12.2	34.8	53.0	0.206
6 weeks[c]	60	10.9	31.1	58.0	0.206
7 weeks[c]	60	10.4	30.3	59.3	0.205
8 weeks[c]	60	10.2	29.4	60.4	0.205
2 months[d]	40	8.2	31.7	60.1	0.205
9 to 10 weeks[c]	60	9.9	30.1	60.0	0.205
10 to 12 weeks[c]	60	9.7	29.0	61.3	0.205
3 months[d]	37	7.9	30.4	61.8	0.205
4 months[d]	41	7.5	31.6	60.9	0.205
Formula-fed[f]					
1 to 12 weeks	60	15.3	26.4	58.3	0.206
Liquid and solid food[g]					
<1 month	6	15.7	21.7	62.7	0.205
1 to 2 months	35	15.6	20.6	63.8	0.205
3 to 5 months	65	21.1	15.7	63.3	0.206
6 to 8 month	74	21.1	17.1	61.8	0.206
9 to 11 months	70	19.8	14.5	65.6	0.205
1 to 4 years	1031	18.5	20.9	60.6	0.206
5 to 11 years	1995	16.6	20.7	62.6	0.206
19 to 19 years	2232	17.3	22.8	59.9	0.206
20 to 39 years	2346	18.9	24.0	57.1	0.206
40 to 64 years	2722	18.8	23.2	58.0	0.206
65+ years	1699	18.0	21.7	60.3	0.206

[a]COH = Carbohydrate.
[b]H_p = postprandial oxygen uptake factor.
[c]Gross (1983).
[d]Butte et al. (1984).
[e]Butte and Calloway (1981).
[f]Gross (1983).
[g]Values for Canadian individuals (NC 1977).

mean physiological daily inhalation rates expressed in m^3/m^2-day begin to decrease linearly only as age increases from the age groups of 10 to <16.5 years for males ($R^2 = 0.92$) and 16.5 to <25 years for females ($R^2 = 0.94$) up to the age group of 65–96 years (Figure 3). Mean daily inhalation rates for boys 0.22 to <16.5 years old (10.99 ± 3.50 to 11.82 ± 3.50 m^3/m^2-day) and girls 0.22 to <10 years of age (10.81 ± 3.29 to 10.83 ± 1.84 m^3/m^2-day) are higher than those for older males and females (8.42 ± 2.13 to 10.93 ± 2.80 and 7.20 ± 1.99 to 9.90 ± 2.50 m^3/m^2 day, respectively). Furthermore, in agreement with our previous study, mean physiological daily inhalation rates in females as well as males aged 25 to <65 years (14.46 ± 3.37 to 20.12 ± 5.03 m^3/day and 0.247 ± 0.061 to 0.289 ± 0.077 m^3/kg-day) are lower than those for normal-weight pregnant and lactating females aged 23–55 years, whose values vary from 19.00 ± 9.98 to 22.31 ± 2.50 m^3/day and 0.297 ± 0.056 to 0.330 ± 0.069 m^3/kg-day (Brochu *et al.* 2006b). Moreover, mean daily inhalation rates in boys (0.428 ± 0.098 to 0.572 ± 0.191 m^3/kg-day) and girls (0.395 ± 0.076 to 0.563 ± 0.180 m^3/kg-day) aged 0.22 to <10 years are higher than the highest means for under-, normal-, overweight, and obese gravid and breastfeeding females aged 11–55 years of 0.385 ± 0.110 and 0.383 ± 0.064 m^3/kg-day, respectively, as reported in Brochu *et al.* (2006b). This is the case in spite of (1) higher VQ means (34.2–36.8) used in the calculation of inhalation rates in pregnant and lactating females compared with those (30.2 and 30.8) in non-gestational and non-lactating individuals and (2) similar mean H values (0.21 and 0.206 L/kcal, respectively).

Based on means and percentiles of physiological daily inhalation rates calculated in the present study, children are generally expected to inhale more air pollutants per unit of weight and BSA (i.e. in µg/kg-day and µg/m^2 day, respectively) than adults during identical exposure concentrations and conditions. The same applies when males are compared with females. The new methodology developed in this study therefore illustrates that some individuals inhale more air on a daily basis (thus more air pollutants) than estimated before. In males 16.5 to <25 years of age, 95th, 97.5th, and 99th percentile values of 28.05, 30.02, and 31.89 m^3/day, respectively, were determined. In males 35 to <45 years old, corresponding percentiles were 29.32, 31.84, and 35.40 m^3/day, respectively. Values from the 95th to 99th percentile in children younger than 1 year of age vary from 0.806 to 1.105 m^3/kg-day in girls and 0.842 to 1.138 m^3/kg-day in boys. These percentiles are 2.8- to 4-folds higher than the inhalation estimate of 0.286 m^3/ kg-day (i.e. 20 m^3/day for a 70-kg adult) adopted by the Federal Register Notices (1980). The same nearly applies to the span of values from the 5th to 99th percentiles (0.328–1.138 m^3/kg-day) for children aged 0.22 to <7 years, and the 10th to 99th percentiles (0.303–0.712 m^3/ kg-day) for those from 7 to <10 years old.

The magnitude of human variability in inhalation values, as reflected by the lowest 1st percentile of 0.105 m^3/ kg-day (data not shown in tables) and the highest 99th percentile of 1.138 m^3/kg-day in males and females aged 2.6 months to 96 years (Tables 9 and 10) corresponds to a factor of 10.9. The inter-individual variability factor of 4.8 was also calculated as the ratio of the highest 95th percentile of 0.937 m^3/kg-day to the lowest 50th percentile of 0.194 m^3/ kg-day. Values for lowest percentiles were always observed in elderly females aged 65 to <96 years and the highest percentile was found in boys aged 2.6 to <6 months. Such inter-individual variability factors for inhalation values (i.e. 4.8–10.9) should be evaluated along with the variability in other pharmacokinetic determinants, in order to assess the adequacy of the default uncertainty factor or the human kinetic adjustment factor (HKAF) currently used in health risk assessment (Renwick 2000; WHO 2005).

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Table 8. Oxygen uptake factor resulting from nutrient intakes for both sexes in different countries.

	Nutrient intake contributions (%)								Oxygen uptake factor[c] (L of O_2/kcal)		
	Males				Females						
Age (years)	*n*	Prot[a]	Fat	COH[b]	*n*	Prot[a]	Fat	COH[b]	Males	Females	Country
1	62	19.6	21.6	58.9	63	20.7	23.0	56.3	0.206	0.207	Australia[d]
1.5	72	18.3	21.4	60.3	70	18.8	21.8	59.4	0.206	0.206	Australia[d]
2	74	17.8	22.1	60.1	72	17.4	21.3	61.2	0.206	0.206	Australia[d]
1 to 2	23	18.1	17.4	64.5	23	17.8	15.1	54.8	0.205	0.206	Finland[e]
2	31	14.7	18.7	66.7	31	15.1	18.7	66.2	0.205	0.205	UK[f]
3	73	16.7	20.6	62.7	72	16.8	21.5	61.7	0.206	0.206	Australia[d]
3	31	15.1	18.3	66.5	42	14.8	19.0	66.2	0.205	0.205	UK[f]
3	153	18.2	19.7	62.1	128	18.3	19.7	62.0	0.206	0.206	Finland[e]
4 to 5	128	16.4	19.0	64.6	139	16.7	19.4	63.8	0.205	0.205	UK[f,g]
6	139	17.5	19.1	63.4	145	17.7	19.8	62.6	0.205	0.206	Finland[e]
6 to 9	130	17.0	20.0	63.0	116	17.0	21.3	61.7	0.205	0.206	USA[h]
7 to 10	25	13.6	19.5	66.8	26	14.2	18.7	67.1	0.205	0.205	UK[i]
9	281	17.6	21.0	61.3	263	17.7	20.9	61.3	0.206	0.206	Finland[j,k]
9.0	434	17.0	19.8	63.3	450	17.0	20.0	63.1	0.205	0.205	Australia[l]
9	133	13.8	37.0	50.0	n.d.	n.d.	n.d.	n.d.	0.207	n.d.	Finland[m]
9	117	13.5	38.0	49.0	n.d.	n.d.	n.d.	n.d.	0.207	n.d.	The Netherlands[m]
9	109	13.4	28.0	57.0	n.d.	n.d.	n.d.	n.d.	0.206	n.d.	Italy[m]
9	114	11.7	16.0	72.0	n.d.	n.d.	n.d.	n.d.	0.204	n.d.	The Philippines[m]
9	116	9.2	22.0	68.0	n.d.	n.d.	n.d.	n.d.	0.204	n.d.	Ghana[m]
9 to 11	196	19.4	21.9	58.7	222	18.9	21.4	59.7	0.206	0.206	USA[n]
11 to 12	76	16.0	20.3	63.8	67	15.7	21.0	63.3	0.205	0.205	UK[i]
12	274	18.0	21.7	60.2	285	17.6	20.8	61.6	0.206	0.206	Finland[j,k]
10 to 12	132	18.9	22.1	59.0	147	16.8	20.8	62.4	0.206	0.206	USA[h]
12 to 14	296	19.4	22.6	57.9	295	19.5	22.6	58.0	0.206	0.206	USA[n]
15	257	18.4	22.2	59.4	264	17.5	20.7	61.8	0.206	0.206	Finland[j,k]
13 to 15	134	18.0	23.0	59.0	110	17.8	22.0	60.2	0.206	0.206	USA[h]
15 to 18	365	20.3	23.4	56.3	374	20.1	23.1	56.8	0.207	0.207	USA[n]
18	217	18.3	22.7	59.0	264	17.5	21.1	61.3	0.206	0.206	Finland[j,k]
16 to 19	96	19.1	24.1	56.8	84	17.1	22.7	60.2	0.206	0.206	USA[h]
21.0	73	19.1	23.7	57.2	82	17.5	21.5	61.0	0.206	0.206	Finland[j,k]
19 to 22	256	22.0	24.6	53.4	300	21.5	24.1	54.4	0.207	0.207	USA[n]
23 to 35	791	21.7	24.8	53.5	952	21.6	23.9	54.5	0.207	0.207	USA[n,o]
24	59	19.9	24.6	55.4	84	18.2	21.5	60.3	0.207	0.206	Finland[j,k]
24 to<35	117	22.2	15.8	62.1	121	23.3	16.5	60.2	0.206	0.206	China[p]
35 to 40	714	22.6	25.6	51.9	838	22.4	24.8	52.9	0.207	0.207	USA[n]
35 to 44	129	21.9	15.7	62.4	134	22.3	15.8	61.9	0.206	0.206	China[p]
40 to 50	171	19.6	14.5	65.9	180	19.2	15.7	65.1	0.205	0.205	Japan[q]
45 to 54	124	22.2	15.2	62.6	127	22.3	14.6	63.1	0.206	0.206	China[p]
51 to 64	579	22.8	25.4	51.7	715	22.6	24.4	53.0	0.207	0.207	USA[n]
55 to 74	130	20.5	13.8	65.7	128	20.7	13.8	65.5	0.205	0.205	China[p]
≤60	449	18.1	16.8	65.2	497	18.1	16.8	65.1	0.205	0.205	Italy[r]
≤60	1583	20.9	22.0	57.1	1935	20.1	20.3	59.6	0.207	0.206	USA[n,r]

n.d. = not determined. [a]Prot = Protein. [b]COH = Carbohydrate. [c]H_p = postprandial oxygen uptake factor. [d]Hitchcock et al. (1984). [e]Räsänen and Ylönen (1992). [f]Payne and Belton (1992). [g]Margarey and Boulton (1984). [h]Morisson et al. (1980). [i]Nelson et al. (1990). [j]Räsänen et al. (1985). [k]Räsänen et al. (1991). [l]Jenner et al. (1988). [m]Knuiman et al. (1983). [n]Pao et al. (1985). [o]Oliveria et al. (1992). [p]Woo et al. (1998). [q]Tokudome et al. (1999). [r]Freudenheim et al. (1993).

The use of H_p, H_p, VQβ, and VQα values as calculated in the present study does not invalidate the conclusions of our previous studies based on calculations using a VQ of 27 and H of 0.21 L of O_2/kcal as constant values: (1) the aggregate errors (under- and overestimations) of daily inhalation estimates and percentiles (in m^3/day and m^3/kg-day) based on published approaches do remain the same (Brochu *et al.* 2006c) and (2) intakes of inhaled air pollutants per unit of body weight (in μg/kg-day) again are expected to be higher in normal-weight males and females compared with their overweight and obese counterparts (Brochu *et al.* 2006a, b).

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Table 9. Distribution percentiles of physiological daily inhalation rates for normal-weight males aged 2.6 months to 96 years.

Age group (years)	Physiological daily inhalation rates[a] Mean ± SD	Percentiles 2.5th	5th	10th	25th	50th	75th	90th	95th	97.5th	99th
(m^3/day)											
0.22 to <0.5	3.76 ± 1.15	2.02	2.20	2.44	2.92	3.57	4.40	5.31	5.97	6.47	7.26
0.5 to <1	4.66 ± 1.34	2.61	2.82	3.11	3.68	4.46	5.45	6.47	7.13	7.74	8.48
1 to <2	5.68 ± 0.85	4.24	4.39	4.61	5.05	5.61	6.25	6.86	7.20	7.45	7.75
2 to <5	7.35 ± 1.39	5.04	5.25	5.57	6.27	7.23	8.31	9.33	9.87	10.24	10.54
5 to <7	9.04 ± 1.21	6.95	7.21	7.54	8.17	8.94	9.81	10.64	11.18	11.68	12.28
7 to <10	11.17 ± 1.89	8.14	8.42	8.84	9.74	10.96	12.35	13.82	14.69	15.40	16.21
10 to <16.5	15.64 ± 3.87	9.82	10.40	11.16	12.74	15.06	17.92	21.04	22.84	24.54	26.72
16.5 to <25	20.39 ± 4.26	13.30	14.15	15.22	17.37	20.04	22.96	25.93	28.05	30.02	31.89
25 to <35	20.00 ± 3.78	13.84	14.54	15.52	17.30	19.55	22.27	25.15	27.00	28.52	30.54
35 to <45	20.12 ± 5.03	12.39	13.24	14.33	16.50	19.41	22.97	26.71	29.32	31.84	35.40
45 to <65	18.41 ± 4.25	11.86	12.60	13.51	15.30	17.80	20.90	24.05	26.39	28.33	30.75
65 to ≤96	15.25 ± 3.78	9.44	10.06	10.90	12.47	14.73	17.50	20.27	22.12	23.91	26.05
(m^3/kg day)[b]											
0.22 to <0.5	0.572 ± 0.191	0.290	0.317	0.356	0.433	0.541	0.677	0.828	0.937	1.040	1.138
0.5 to <1	0.536 ± 0.166	0.288	0.312	0.344	0.414	0.509	0.634	0.759	0.842	0.922	1.015
1 to <2	0.537 ± 0.095	0.379	0.397	0.420	0.467	0.527	0.599	0.666	0.708	0.747	0.787
2 to <5	0.493 ± 0.125	0.297	0.317	0.345	0.400	0.477	0.568	0.663	0.726	0.777	0.845
5 to <7	0.463 ± 0.077	0.332	0.349	0.368	0.407	0.456	0.511	0.564	0.597	0.631	0.668
7 to <10	0.428 ± 0.098	0.275	0.290	0.312	0.357	0.416	0.485	0.560	0.609	0.653	0.712
10 to <16.5	0.383 ± 0.131	0.191	0.211	0.237	0.288	0.362	0.454	0.556	0.628	0.702	0.790
16.5 to <25	0.290 ± 0.065	0.184	0.197	0.213	0.244	0.283	0.330	0.377	0.406	0.435	0.473
25 to <35	0.282 ± 0.059	0.187	0.198	0.212	0.239	0.275	0.317	0.361	0.390	0.417	0.445
35 to <45	0.289 ± 0.077	0.173	0.185	0.203	0.234	0.278	0.333	0.389	0.429	0.470	0.523
45 to <65	0.259 ± 0.065	0.161	0.171	0.184	0.212	0.249	0.296	0.346	0.378	0.408	0.449
65 to ≤96	0.225 ± 0.059	0.134	0.144	0.157	0.182	0.216	0.259	0.303	0.333	0.360	0.400
(m^3/m^2 day)[b]											
0.22 to <0.5	10.99 ± 3.50	5.74	6.26	7.00	8.46	10.44	12.97	15.76	17.60	19.49	21.51
0.5 to <1	11.24 ± 3.34	6.15	6.69	7.41	8.80	10.74	13.15	15.70	17.42	18.96	21.15
1 to <2	11.68 ± 1.91	8.42	8.83	9.30	10.28	11.51	12.91	14.25	15.06	15.79	16.59
2 to <5	11.54 ± 2.61	7.32	7.78	8.40	9.58	11.26	13.18	15.11	16.27	17.36	18.52
5 to <7	11.53 ± 1.72	8.59	8.96	9.43	10.30	11.39	12.61	13.83	14.58	15.29	16.11
7 to <10	11.55 ± 2.27	7.94	8.33	8.86	9.88	11.28	12.94	14.61	15.74	16.71	17.75
10 to <16.5	11.82 ± 3.50	6.64	7.13	7.83	9.26	11.22	13.77	16.61	18.44	20.17	22.29
16.5 to <25	10.92 ± 2.35	7.02	7.48	8.08	9.23	10.73	12.33	13.96	15.11	16.22	17.45
25 to <35	10.64 ± 2.12	7.21	7.63	8.12	9.12	10.40	11.89	13.52	14.50	15.43	16.50
35 to <45	10.93 ± 2.80	6.63	7.11	7.73	8.90	10.53	12.48	14.64	16.05	17.43	19.31
45 to <65	9.88 ± 2.36	6.28	6.63	7.15	8.16	9.56	11.25	12.99	14.24	15.32	16.92
65 to ≤96	8.42 ± 2.13	5.14	5.50	5.95	6.86	8.12	9.67	11.23	12.25	13.29	14.78

SD = standard deviation.

[a]Daily inhalation rates = [(SMR × H_F × VQβ × Sld) + (Eα × H_P × VQα)× (24– Sld)] × 0.06, and SMR = [(BEE × F_{sleep}) + ECG]/1440, Eα = [(TDEE–BEE)/((24– Sld) × 60)] + (BEE + ECG)/1440. BEE, ECG, TDEE (kcal/day) and Sld (h/day) are defined and given in Tables 1, 2 and 5. VQβ and VQα (unitless) are defined and reported in Table 3. SMR = sleeping metabolic rate (kcal/min). F_{sleep} is a correcting factor of BEE values. F_{sleep} = 0.960 ± 0.023, minimum = 0.870, maximum = 1.039. H_F and H_P = oxygen uptake factor during fasting and postprandial phases, respectively (L of O_2/kcal). H_F = 0.2057 ± 0.0018 L/kcal, minimum = 0.198 L/kcal, maximum = 0.214 L/kcal. H_P = 0.2059 ± 0.0019 L/kcal, minimum of 0.199 L/kcal, maximum of 0.221 L/kcal.

[b]Daily inhalation rates were divided by body weights and body surface areas reported in Tables 1 and 2 in order to obtain values expressed in m^3/kg min and m^3/m^2 min, respectively.

H values

High intakes of carbohydrates and a low level of proteins ingested led to lower H_P values (0.203–0.204 L of O_2/kcal) in subjects (n = 17 993) living in Ghana, the Philippines, and Vietnam, compared with those from other countries (0.205–0.208 L of O_2/kcal; n = 101,686). However, the magnitude of H_P values is unaffected by an individuals' age, gender, or BMI for subjects living in a given country (n = 119 679). Rather, it is the variability of the food intake components that determines the magnitude of H_P values. However, such variability is found to have little effect on the magnitude of physiological daily inhalation

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Table 10. Distribution percentiles of physiological daily inhalation rates for normal-weight females aged 2.6 months to 96 years.

	Physiological daily inhalation rates[a]										
		Percentiles									
Age group (years)	Mean ± SD	2.5th	5th	10th	25th	50th	75th	90th	95th	97.5th	99th
(m^3/day)											
0.22 to <0.5	3.63 ± 1.07	2.03	2.19	2.41	2.86	3.47	4.25	5.07	5.64	6.15	6.72
0.5 to <1	4.30 ± 1.26	2.35	2.57	2.84	3.37	4.13	5.02	6.00	6.62	7.24	8.07
1 to <2	5.43 ± 0.90	3.79	3.97	4.22	4.76	5.41	6.07	6.64	6.96	7.18	7.39
2 to <5	6.90 ± 1.25	4.87	5.06	5.34	5.94	6.77	7.72	8.62	9.20	9.62	9.99
5 to <7	8.59 ± 1.12	6.66	6.88	7.19	7.75	8.50	9.32	10.10	10.58	11.03	11.49
7 to <10	10.71 ± 1.62	7.94	8.27	8.71	9.54	10.57	11.75	12.89	13.64	14.28	14.94
10 to <16.5	13.32 ± 3.06	8.49	9.02	9.67	11.02	12.98	15.17	17.43	18.96	20.35	21.92
16.5 to <25	16.46 ± 3.21	11.19	11.76	12.61	14.16	16.13	18.38	20.69	22.20	23.59	25.22
25 to <35	15.82 ± 3.05	10.83	11.38	12.11	13.65	15.52	17.64	19.88	21.34	22.73	24.35
35 to <45	16.21 ± 4.02	9.99	10.69	11.55	13.31	15.61	18.51	21.68	23.55	25.57	27.90
45 to <65	14.46 ± 3.37	9.04	9.67	10.45	12.05	14.08	16.47	18.91	20.49	22.10	24.00
65 to ≤96	11.51 ± 3.04	6.84	7.32	7.97	9.30	11.07	13.25	15.56	17.29	18.62	20.54
(m^3/kg day)[b]											
0.22 to <0.5	0.563 ± 0.180	0.299	0.326	0.360	0.431	0.534	0.662	0.807	0.897	0.994	1.105
0.5 to <1	0.510 ± 0.159	0.269	0.295	0.329	0.393	0.486	0.601	0.722	0.806	0.882	0.979
1 to <2	0.516 ± 0.105	0.336	0.356	0.384	0.438	0.510	0.582	0.659	0.704	0.740	0.785
2 to <5	0.492 ± 0.124	0.288	0.311	0.341	0.400	0.480	0.568	0.661	0.716	0.766	0.826
5 to <7	0.441 ± 0.076	0.313	0.328	0.349	0.386	0.434	0.488	0.545	0.579	0.609	0.642
7 to <10	0.395 ± 0.076	0.267	0.284	0.303	0.340	0.388	0.443	0.497	0.531	0.564	0.601
10 to <16.5	0.306 ± 0.089	0.170	0.185	0.204	0.241	0.293	0.358	0.427	0.471	0.514	0.566
16.5 to <25	0.275 ± 0.059	0.180	0.190	0.206	0.234	0.269	0.310	0.352	0.380	0.408	0.444
25 to <35	0.273 ± 0.060	0.176	0.187	0.201	0.230	0.266	0.310	0.354	0.383	0.410	0.443
35 to <45	0.277 ± 0.072	0.166	0.179	0.194	0.225	0.266	0.318	0.373	0.410	0.443	0.480
45 to <65	0.247 ± 0.061	0.150	0.161	0.176	0.203	0.239	0.282	0.328	0.358	0.387	0.420
65 to ≤96	0.202 ± 0.059	0.114	0.124	0.136	0.160	0.194	0.235	0.281	0.311	0.344	0.385
(m^3/m^2 day)[b]											
0.22 to <0.5	10.81 ± 3.29	5.90	6.38	7.02	8.42	10.29	12.62	15.29	17.03	18.65	20.37
0.5 to <1	10.55 ± 3.18	5.71	6.22	6.85	8.23	10.08	12.40	14.77	16.40	17.99	20.00
1 to <2	11.14 ± 2.06	7.47	7.91	8.49	9.61	11.04	12.55	13.93	14.74	15.40	16.10
2 to <5	11.24 ± 2.53	7.12	7.59	8.19	9.36	10.95	12.84	14.66	15.89	16.97	18.04
5 to <7	10.98 ± 1.67	8.12	8.49	8.93	9.77	10.84	12.03	13.24	14.00	14.60	15.41
7 to <10	10.83 ± 1.84	7.68	8.10	8.56	9.49	10.67	12.00	13.29	14.13	14.81	15.58
10 to <16.5	9.67 ± 2.50	5.84	6.23	6.77	7.83	9.35	11.14	13.03	14.29	15.48	16.88
16.5 to <25	9.84 ± 2.00	6.59	6.97	7.45	8.41	9.61	11.00	12.51	13.43	14.35	15.35
25 to <35	9.73 ± 2.01	6.43	6.84	7.33	8.30	9.52	10.93	12.41	13.32	14.27	15.27
35 to <45	9.90 ± 2.50	6.05	6.48	7.01	8.11	9.56	11.32	13.26	14.53	15.76	17.15
45 to <65	8.88 ± 2.12	5.46	5.87	6.35	7.35	8.62	10.12	11.69	12.75	13.67	15.00
65 to ≤96	7.20 ± 1.99	4.22	4.52	4.92	5.76	6.92	8.33	9.87	10.88	11.93	13.15

SD = standard deviation.

[a]Daily inhalation rates = [(SMR × H_F × VQβ × Sld) + (Eα × H_P × VQα) × (24– Sld)] × 0.06, and SMR = [(BEE × F_{sleep}) + ECG]/1440, Eα = [(TDEE–BEE)/((24– Sld) × 60)] + (BEE + ECG)/1440. BEE, ECG, TDEE (kcal/day) and Sld (h/day) are defined and given in Tables 1 ,2 and 5. VQβ and VQα (unitless) are defined and reported in Table 3. SMR = sleeping metabolic rate (kcal/min). F_{sleep} is a correcting factor of BEE values. F_{sleep} = 0.960 ± 0.023, minimum = 0.870, maximum = 1.039. H_F and H_P = oxygen uptake factor during fasting and postprandial phases, respectively (L of O_2/kcal). H_F = 0.2057 ± 0.0018 L/kcal, minimum of 0.198 L/kcal, maximum of 0.214 L/kcal. H_P = 0.2059 ± 0.0019 L/kcal, minimum of 0.199 L/kcal, maximum of 0.221 L/kcal.

[b]Daily inhalation rates were divided by body weights and body surface areas reported in Tables 1 and 2 in order to obtain values expressed in m^3/kg min and m^3/m^2 min, respectively.

rates. The use of the lowest H_P value of 0.203 L of O_2/kcal for Vietnamese subjects (n = 17,763) and the highest H_P value of 0.208 L of O_2/kcal for American and French subjects (n = 77,278), instead of the H_P value of 0.2059 L of O_2/kcal that was used in this study, would have changed the physiological daily inhalation rates by only –1.2% to +0.9%. This is due to the fact that H_P and H_F values (i.e. 0.2059 and 0.2057 L of O_2/kcal, respectively) both rest in the middle of the span between the lower Vietnamese (i.e. 0.203 L of O_2/kcal) and higher American (i.e. 0.208 L of O_2/kcal) values. Several thousand sets of VO_2 and VCO_2 values (data not shown in tables; n = 6696) measured in

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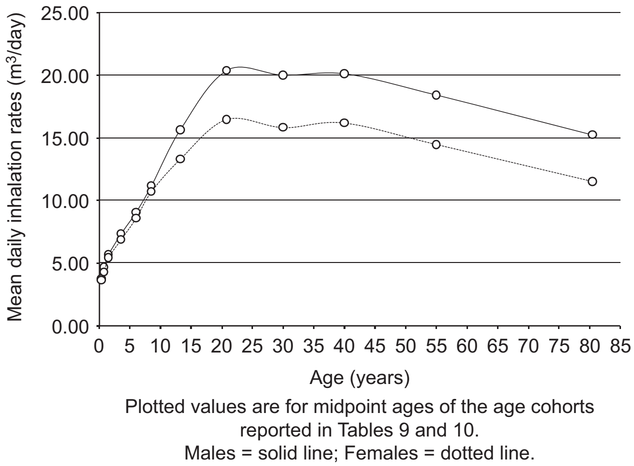

Figure 1. Mean daily inhalation rates (m^3/day) in normal-weight males and females as a function of age.

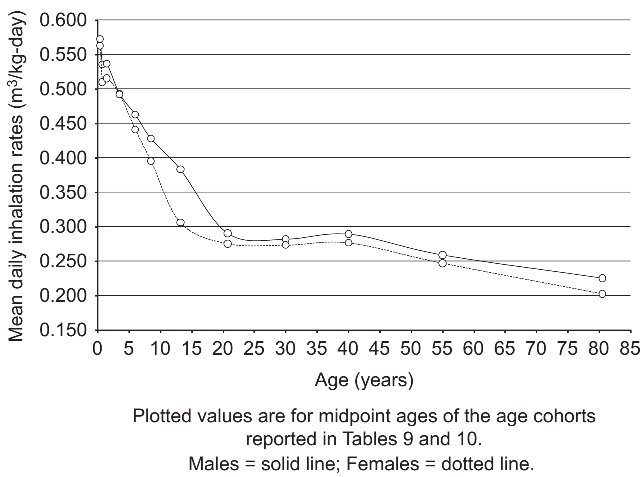

Figure 2. Mean daily inhalation rates (m^3/kg day) in normal-weight males and females as a function of age.

subjects during strenuous exercise when consuming higher oxygen rates (0.82–5.48 L/min) than upper $VO_2\beta$ and $VO_2\alpha$ limits would have biased *H* values that were included in the present study.

VQ values

For a given age group, VQ values during anaerobiosis were found to be higher than values for VQβ, VQα, and VQ for VO_2 demands below the anaerobic threshold ranging from 0.54 to 1.81 L/min. Former VQ values were calculated by using VE values measured in subjects performing strenuous exercises during high oxygen uptake rates varying from 0.86 to 4.47 L/min in children aged 1 to <16.5 years and 3.00 to 5.63 L/min in individuals 16.5–96 years of age, respectively. During such periods of exertion, the aerobic metabolism becomes inadequate to supply all energy required and is compensated by the anaerobic metabolism (Guyton 1991). However, these punctual VE values as well as those used for the calculation of VQ values below the anaerobic threshold have little influence on physiological daily inhalation rates, since $VO_2\alpha$ values during the aggregate daytime activities for subjects

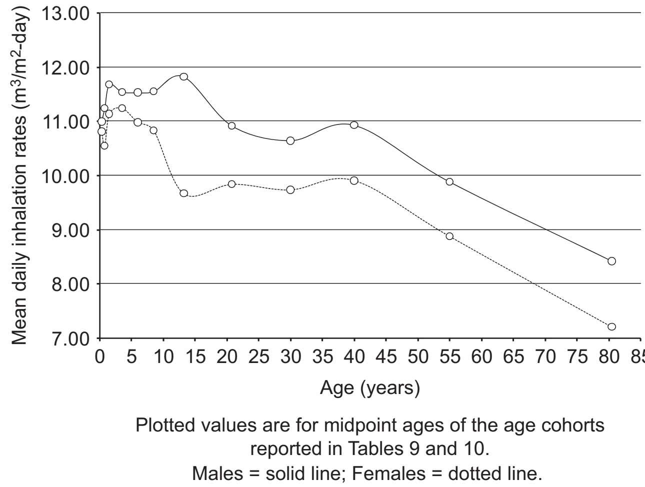

Figure 3. Mean daily inhalation rates (m^3/m^2 day) in normal-weight males and females as a function of age.

aged 2.6 months to 96 years were found to vary only from 0.06 to 0.81 L/min. The performance of activities under anaerobic conditions can be considered to correspond, in the reality of each day, to sufficiently rare events of short durations; the latter are therefore diluted in the large aerobic process of oxygenation, which is continuously effective during the aggregate daytime activities as well as on a 24-h basis. Consequently, values for VQ during anaerobiosis would have overestimated physiological daily inhalation rates, while most of those during sub-anaerobiosis would have underestimated such rates.

Conclusion

This study presents an exhaustive compilation and critical analysis of a wide range of published data related to *H* and VQ values. It supports the establishments of solid bases for the appropriate selection and use of input data in the determination of daily inhalation rates. By the same occasion, it contributes to improve our previous procedure based on DLW measurements (Brochu *et al.* 2006a–c) due to the fact that it is now possible to determine and integrate nighttime and daytime respiratory parameters into the physiological daily inhalation calculation process. Only data measured in healthy subjects during VO_2 demands within the span of $VO_2\beta$ and $VO_2\alpha$ values based on DLW measurements were used in the present study in order to determine H_F and VQβ values for nighttime sleep (fasting phase) as well as H_P and VQα values for aggregate daytime activities (postprandial phase), respectively. This innovative strategy has allowed for the exclusion of inadequate published data in the calculation of physiological daily inhalation rates measured in >19,000 subjects. Values for H_F, VQβ, H_P, and VQα were combined into the daily inhalation rates calculation process with BEE from indirect calorimetry measurements ($n = 1235$) as well as ECG and TDEE values based on DLW methodology covering an aggregate period of >19,000 days. In the worst case scenario, simultaneous minimal and maximal mean errors associated

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with *H*, BEE, ECG, and TDEE values could have a combined effect varying from –3.0% to +2.3% on the accuracy of physiological daily inhalation values. This span of potential errors is insignificant compared with those based on time–activity ventilation, food-energy intakes, metabolic equivalents, and Parameter A approaches (Brochu *et al*. 2006c), which vary from –49% to +122% for some 24-h breathing estimates. Body weight and height, as well as BEE and TDEE values that have been systematically measured for each subject during DLW measurements have assured a precise calculation of inhalation rates per unit of weight and BSA in the present study. Mean and percentile physiological daily inhalation rates expressed in m^3/m^2-day have never been determined before for individuals as a function of age. The information presented strongly suggests that the mean and percentile physiological daily inhalation values reported in this study correspond to the most precise inhalation values (in m^3/day, m^3/kg-day, and m^3/m^2-day) in current literature, and are thereby relevant for use in health risk assessment.

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Declaration of interest

The authors report no conflicts of interest.

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Appendix

VO_2 and VE measurements reported in the following studies were used to calculate the VQ values of Table 8. Values for VO_2 and VCO_2 taken from the underlined references were also used to determine the *H* values.

Individual data from Robinson (1938), Åstrand (1952), Cohn *et al.* (1954), Cook *et al.* (1955), Craig (1955), Stahlman and Meece (1957), Åstrand *et al.* (1959), Åstrand and Saltin (1961a, b), Becklake *et al.* (1962), Donevan *et al.* (1962), Nelson *et al.* (1962), Newman *et al.* (1962), Andersen and Hart (1963), Cander and Hanowell (1963), Mostyn *et al.* (1963), Pugh (1964), Tabakin *et al.* (1964), Michael and Horvath (1965), Damato *et al.* (1966), Karlsson *et al.* (1967), Ekblom *et al.* (1968), Pierce *et al.* (1968), Murphy *et al.* (1969), Ouellet *et al.* (1969), Costill *et al.* (1971), Holmér (1972), Bachofen *et al.* (1973), Casaburi *et al.* (1977), Kobayashi *et al.* (1978), Jones *et al.* (1979), Frostell *et al.* (1983), Martin *et al.* (1982), Torre-Bueno *et al.* (1985), Babb and Rodarte (1993), Eldridge *et al.* (2004), and Ong *et al.* (2004).

Mean values and standard deviations were from Åstrand (1960), Brouha *et al.* (1960), Durnin *et al.* (1960), Froeb (1962), Raine and Bishop (1963), Naimark *et al.* (1964), Andersen and Hermansen (1965), Becklake *et al.* (1965), Hermansen and Andersen (1965), Andrew *et al.* (1966), Malmberg (1966), Knuttgen (1967), Sinning and Adrian (1968), Ekblom (1969), Hermansen and Saltin (1969), Whipp and Wasserman (1969), Dixon and Faulkner (1971), Eriksson *et al.* (1971), Godfrey et al. (1971), Pollock *et al.* (1971), Krone *et al.* (1972), Miyamura and Honda (1972), Åstrand *et al.* (1973), Hanson (1973), Koch and Eriksson (1973), Davies *et al.* (1975), Drinkwater *et al.* (1975), Stamford (1975), Kearney *et al.* (1976), Weber *et al.* (1976), Sharma *et al.* (1977), Sidney and Shephard (1977), Yamaji and Miyashita (1977), Fohlin *et al.* (1978), Kanstrup and Ekblom (1978), Davis *et al.* (1979), Plowman *et al.* (1979), Segal and Brooks (1979), Heath *et al.* (1981), Inbar *et al.* (1981), Sargeant *et al.* (1981), Ehrsam *et al.* (1982), Flandrois *et al.* (1982), Miyamoto *et al.* (1982), Nery *et al.* (1982), Zimmerman *et al.* (1982), Buchfuhrer *et al.* (1983), Heigenhauser *et al.* (1983), Lewis *et al.* (1983), Toner *et al.* (1983), Anton-Kuchly *et al.* (1984), Veicsteinas *et al.* (1984), Andersen *et al.* (1985), Hagberg *et al.* (1985), Yerg *et al.* (1985), Joyner *et al.* (1986), Vogel *et al.* (1986), Wagner *et al.* (1986), Caiozzo *et al.* (1987), Hagberg *et al.* (1988), Sue *et al.* (1988), Bebout *et al.* (1989), Miyamoto *et al.* (1989), Makrides *et al.* (1990), Marti and Howald (1990), Rogers *et al.* (1990), Babb *et al.* (1991), Blackie *et al.* (1991), Kohrt *et al.* (1991), Roca *et al.* (1992), Kastello *et al.* (1993), Stevenson *et al.* (1994), Kasch *et al.* (1995), McClaran *et al.* (1995), Rowland and Boyajian (1995), Gore *et al.* (1996), Podolsky *et al.* (1996), Proctor and Beck (1996), Rowland and Cunningham (1997), Tanaka *et al.* (1997), Harms *et al.* (1998), Marven *et al.* (1998), Putman *et al.* (1998), Katayama *et al.* (1999), Pellegrino *et al.* (1999),, Hunter *et al.* (2000), Nottin *et al.* (2000), Loftin *et al.* (2001), Riddell *et al.* (2001), Schiller *et al.* (2001), Poole *et al.* (2002), Neder *et al.* (2003), Ocel *et al.* (2003), Pimentel *et al.* (2003), Volianitis *et al.* (2003), Olfert *et al.* (2004), Petersson *et al.* (2004), Nourry *et al.* (2005), Osborne and Schneider (2005), Stickland *et al.* (2006), and Woo *et al.* (2006).

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